

Laser Absorption Spectrometer Concept for Global-Scale Observations of Atmospheric Carbon Dioxide

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ABSTRACT

A laser absorption spectrometer concept is described for high precision measurements of CO₂ mixing ratio in the troposphere. The approach is based on measurement of integrated path differential absorption at selected frequencies within a CO₂ absorption band near 2.05 μm . Coherent detection is used to attain high sensitivity to the return signal backscattered from the surface.

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Introduction

The global carbon cycle is attracting increasing attention both scientifically and politically. The chief societal objective is to stabilize greenhouse gas concentrations, with particular attention given to CO₂. This demands accurate assessment of the total source of CO₂ to the atmosphere. Attempts to improve understanding of the spatial structure of carbon sources are inherent in this assessment. Scientific objectives include four categories that can be addressed using space-based observations on a global scale [Sarmiento and Wofsy, 1999]: (1) oceanic vs. terrestrial sinks of CO₂; (2) net sources (or sinks) of CO₂ over continental scale regions and the various oceans; (3) interhemispheric transport of atmospheric CO₂; and (4) interannual variability in regional exchange of CO₂. Each objective represents a key component of coupled carbon models that is not presently well constrained by existing carbon dioxide measurement data.

Observations of carbon dioxide mixing ratios from Earth orbit, primarily in the lower and middle troposphere with measurement precision equivalent to about 2 ppmv, are desired to define spatial gradients of CO₂, from which sources and sinks can be derived and quantified. Data would be needed over a wide distribution of latitude, with spatial resolution sufficient to provide global monthly mean values on a spatial scale of order 10⁶ – 10⁷ km².

An active sensing approach using tunable IR lasers offers several advantages over other potential techniques. Passive techniques for retrieving carbon dioxide distributions may include spectral radiometers operating in the CO₂ thermal IR bands, or spectrometers observing scattered solar radiation in the near infrared absorption bands. The former technique is extremely sensitive to uncertainties in knowledge of the temperature profile, and a cooled instrument would be required, but the instrument could operate day and night. The latter technique [Rayner and O'Brien, 2001], making use of observations in the sun-glint regions over the oceans, has the potential to achieve the required signal-to-noise ratio (SNR). Obviously this would be limited to daytime observations over the oceans and would require a more lengthy period to build up complete maps over the oceans. Laser techniques include integrated path differential absorption, using the surface to provide the backscattered signal, or full-up DIAL,

using the atmospheric aerosol to provide the backscatter in a range-gated mode. Here we concentrate on the former approach and describe a laser absorption spectrometer instrument that has the potential to achieve the required precision. Analysis of this approach for atmospheric profiling of trace gases dates to the mid-1970's [Menzies and Chahine, 1974], and an aircraft instrument utilizing this approach to measure regional ozone transport was described in Shumate *et al.* [1981].

There exist several challenges to global-scale Earth-orbiting observations of carbon dioxide, and in addition extensive correlative measurements using well-calibrated ground-based and airborne sensors would be required in order to transform measurement precision into an acceptable level of accuracy. The presence of clouds limits the observing opportunities, and thin cirrus in particular can potentially delude the retrieval algorithms. Aerosol scattering in the boundary layer, and in elevated layers, complicate the measurement retrieval interpretation. A DIAL instrument with sufficient sensitivity to obtain the required measurement precision would detect even sub-visible cirrus in the path. Obviously the aerosol scattering layers would appear also. However the DIAL approach, being directly dependent on the aerosol backscatter, is influenced by small-scale inhomogeneities in the aerosol spatial distributions. For all approaches the temperature profile must be well known. Also the surface pressure, or alternatively the profile of oxygen or nitrogen density, must be well known.

Instrument description

An Earth-orbiting instrument concept will be described, followed by brief comments on an analogous aircraft instrument.

The integrated path differential absorption (IPDA) technique can utilize either CW or pulsed transmitter; we emphasize CW here because of its relative simplicity. For an instrument operating from low Earth orbit (LEO) the required power-aperture product ranges from 0.5 – 1.5 W-m² depending on altitude. Figure 1 indicates required transmitter power over ocean surfaces assuming a 0.5-m diameter receiver aperture, along with typical coherent detection efficiency factors. The two altitudes span the range of typical LEO altitudes, with the lower end of the range obviously being favorable in terms of required active sensing instrument mass and power.

The assumed round-trip atmospheric transmittance is 0.25 and the pointing is 3-degrees off-nadir. We assume sufficient SNR to achieve a 0.3% measurement precision from the instrument itself, not including other contributions to the error budget. The global average surface wind speed is near 7 m/s. Middle and high latitude surface wind speeds are usually higher. At a minimum the instrument should be able to operate with surface wind speeds up to 10 m/s. The ocean surface retroreflectance for this value of surface wind speed is near 0.1 sr^{-1} . Over land surfaces the (ρ/π) factor is near 0.1 sr^{-1} or above for vegetation in semi-arid regions, dry soils, and deserts [Kaufman *et al.*, 1997; Kaufman *et al.*, 2000], and for snow and ice. In lidar applications the “hot spot” effect (retroreflectance enhancement) often adds significantly to the reflectance that one would assume based on the albedo of the surface and a Lambertian model.

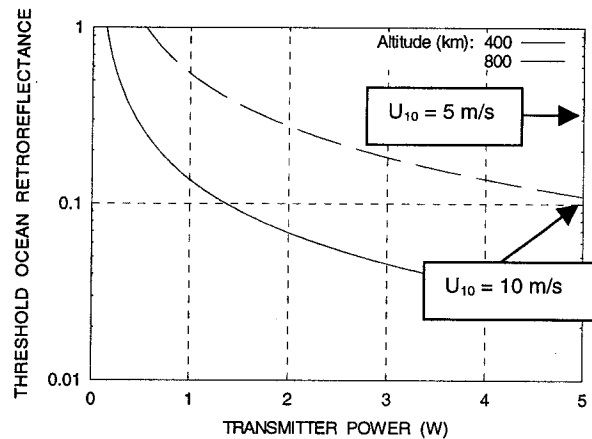


Figure 1. Dependence of threshold ocean surface retroreflectance on transmitter power, altitude, and surface wind speed, U_{10} , for the assumed instrument parameters.

To achieve sufficient sensitivity, narrow receiver bandwidth is essential. Here we have assumed a bandwidth of 10 kHz, compared with a 2-kHz lower limit on the signal spectral width due to the decorrelation time of the surface reflection signal. This places a requirement on the transmitter short-term (msec) jitter as well as the angular rate of change of the spacecraft attitude. Spacecraft angular drift effects can be removed (compensated) by use of a frequency-agile RF local oscillator (LO) in the second-IF domain.

Table 1 provides a summary of the salient characteristics of the LAS CO_2 instrument, assuming a 450-km altitude. The concept includes two transmitter lasers, the second being at the fixed off-line frequency with output power requirement reduced by the CO_2 optical depth factor.

PARAMETER	VALUE
Spectral Region	2.05, 2.07 μm
Transmitter Power	2 W
Receiver aperture	0.5 m
Beam divergence	10 μrad
Receiver bandwidth	10 kHz
Along-track resolution	100 km

Table 1. LAS instrumental operating characteristics.

Required ancillary data

To achieve overall measurement precision at the 0.5% level, the atmospheric column being probed must be well characterized. The measurement objective is the carbon dioxide volume mixing ratio. A sufficiently accurate spectroscopic measurement must rely on an accurate temperature profile, since the line intensity and linewidth are temperature dependent. An accurate temperature profile as well as an accurate surface pressure can be combined to provide the pressure and density profiles, assuming hydrostatic equilibrium. In lieu of surface pressure, an accurate profile of oxygen or nitrogen may serve as a proxy for an atmospheric density profile. Only a very few lines in a typical P- or R-branch of a band provide sufficiently low susceptibility to uncertainties in temperature over a range of tropospheric temperatures to maintain this source of error at a reasonably small fraction of the total error budget. (This is the subject of a separate paper.) The best temperature profiler available in the present era, the Atmospheric Infrared Sounder [AIRS; Aumann and Pagano, 1994], is expected to provide accuracy to 1 K rms with 1 km vertical resolution. (AIRS is scheduled to be launched in late 2001, beginning a 5-yr lifetime mission.) Including an AIRS-class instrument in the payload would increase mission costs substantially. An alternative is to formation fly with AIRS or an equivalent capability AIRS follow-on. Another alternative is to rely on the numerical weather prediction model analyses, which should provide profiles with $\pm 2 \text{ K}$ accuracy over most of the globe during the next decade when an AIRS-class sounder is in orbit. The same NWP analyses would provide the surface pressure maps. Surface pressure accuracy is expected to be about 2 hPa rms over most of the globe, i.e., 0.2% rms.

The ideal spectral line to use for the differential absorption sounding will provide the optimum combination of optical depth and insensitivity to temperature profile uncertainties, for the offset tuning required to provide a weighting function peaking at the desired middle or lower tropospheric altitude. This translates into a requirement on the CO_2 band strength. The $2\nu_1 + \nu_3$ band in the 2.05-2.07 μm region is at the

upper end of the useful range of band strengths. (The $2\nu_1 + 2\nu_2^0 + \nu_3$ band near $1.58\text{ }\mu\text{m}$ is at the lower end.) Suitable lines in this band can be used to provide weighting functions which effectively interact with the lower troposphere, peaking at or near the surface.

Clouds and aerosol layers of significant optical thickness must be recognized in the instrument field-of-view. They effectively alter the atmospheric sounding thickness of the column through the extinction and backscattering processes, rendering perturbations to the altitude weighting function. A climatological model of the boundary layer aerosol may suffice to maintain this potential error source within bounds, but further study of this approach is necessary. Adding a laser altimeter to the payload would provide a means of "flagging" the conditions for which accurate retrievals of the lower tropospheric carbon dioxide are not possible. A visual scene camera and a thermal IR imager would be an important addition to provide the necessary contextual information. An oxygen A-band spectrometer might be sufficient to provide the cloud and aerosol information during daytime portions of the orbits. Alternatively a pulsed version of the CO₂ LAS instrument, using an injection-seeded transmitter, may be employed. The effectiveness of various instrument combinations in discerning the clouds and aerosol layers must be carefully modeled in simulations.

Summary

A laser absorption spectrometer instrument employing a coherent detection receiver appears to be a feasible means for providing global-scale carbon dioxide mixing ratios in the lower troposphere with sufficient precision to contribute to the carbon cycle scientific objectives. It is likely that other sensors in the same payload, and possibly formation flying with a satellite carrying a high accuracy temperature profiler, will be necessary in order to achieve the precision requirement and minimize potential biases. Transforming precision to accuracy will require extensive correlative measurements using ground-based and airborne CO₂ measurement techniques with an historical record of demonstrated accuracy.

An aircraft instrument would permit the demonstration of the LAS approach under a variety of atmospheric and surface conditions. A 100-200 mW transmitter would suffice for such an instrument. This would be viewed by many as an essential stepping-stone in the development of a credible approach to a global-scale measurement.

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